

Session 4

Rotating Detonation Engine Research at NRL

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ROTATING DETONATION ENGINE RESEARCH AT NRL

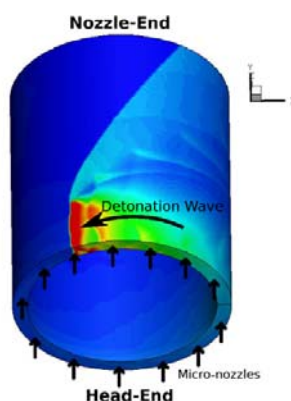
K. Kailasanath and D.A. Schwer

Laboratories for Computational Physics & Fluid Dynamics,
U.S. Naval Research Laboratory, Washington DC

*International Workshop on Detonation for Propulsion
July 26-28, 2013*



Focus is on **Idealized** “Engine or Device” Configuration



How does considering finite-rate Chemical Kinetics in the expansion region change RDE performance. Can this model be used to investigate pollutant formation?

Several groups around the world are doing modeling and experimental studies of RDEs (Bykovskii, Wolanski, Falempin, Hayashi, Schauer, Yi, Wang, Brophy, Wu, Clafin, Smith, Tsuboi, Frolov, et al.)

Recent RDE Studies at NRL

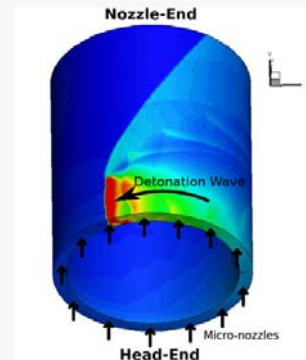
- Flow-field description (2010 International Combustion Symposium)
- Stagnation/back pressure effect (JPC 2010-6880)
- Engine sizing effect (AIAA 2011-0581)
- Three-dimensionality effect
- Simulation of Specific rigs
- Various Fuels (2012 International Combustion Symposium)
- Injection/inflow effects (JPC 2011-6044; ASM 2012-0617, ASM 2013-1178)
- Exhaust flow (JPC 2012-3943)
- Expansion Flow Chemistry
- Preliminary Fuel-Air Mixing studies
- “Propel” -- More Efficient Complex Configuration Simulation Capability



BASELINE SOLUTION

- **Baseline configuration**

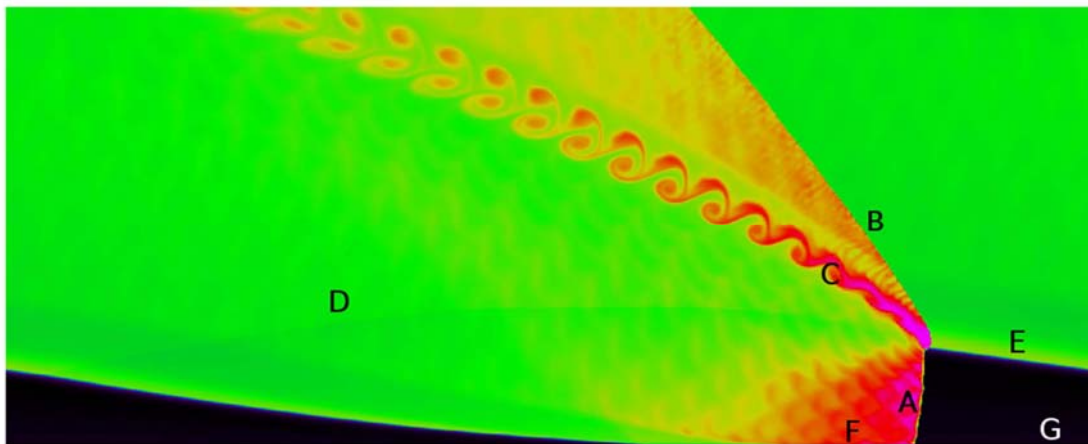
- Stoichiometric hydrogen-air RDE of Wolanski and coworkers*
- Geometry
 - Ratio of inlet nozzle throat area to wall is 0.2
 - 14 cm inner and 16 cm outer diameter (1 cm thickness)
 - 17.7 cm axial length
- Flow conditions
 - Hydrogen-air at stoichiometric conditions
 - Inflow at 10 atm stagnation pressure
 - 300 K stagnation temperature
 - Back pressure of 1 atm



*Yi, T-H, Turangan, C., Lou, J., Wolanski, P., and Kindracki, J. "A Three-Dimensional Numerical Study of Rotational Detonation in an Annular Chamber," AIAA Paper 2009-634, Aerospace Sciences Meeting, Orlando, FL, 2009.

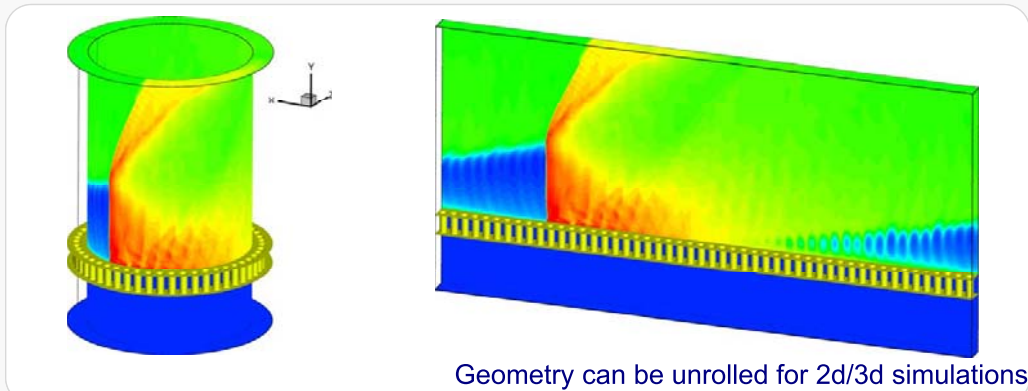


Typical Rotating Detonation Wave Structure



- A- Detonation Wave B- Oblique Shock Wave D- Secondary Shock Wave
C- material slip line between freshly detonated products and older products
E- Mixing region between fresh detonable mixture and detonated gases
F- Region with blocked micro-nozzles, G- detonable mixture injected from micro-nozzles

MODELING ROTATING DETONATION ENGINES



Geometry can be unrolled for 2d/3d simulations

- Euler equations with multi-species mixture model, induction time parameter model
- Exit boundary is mixture of supersonic/subsonic boundary with specified back pressure
- Typical small radial width of combustion chamber compared to diameter allows us to rollout the chamber to a two-dimensional geometry
- Domain extends to include plenum, injection plate
- Model does not permit flame propagation into the mixture plenum
- Inlet boundary is held at constant stagnation pressure and temperature

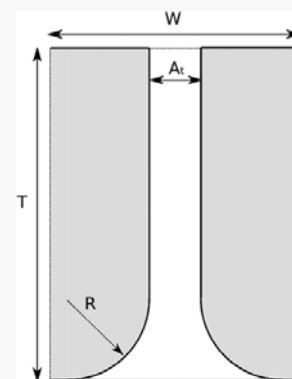
Are these BC good enough ? Do they capture potential back-flow, pressure feedback, swirl in exhaust.

Fundamental study to look at Ratio between injector throat area and injection plate area to see how it impacts performance, feedback

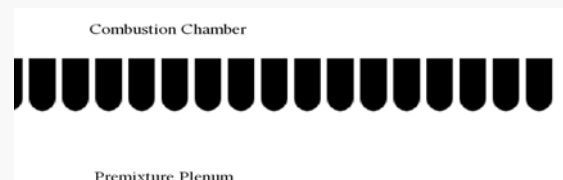


INJECTION MODELING

- **Injector face**
 - Injector face typically is a thick plate between the combustion chamber and premixture or fuel and oxidizer plenums.
 - Micro-nozzles inject high pressure fluid from the plenums to the combustion chamber.
 - The detonation wave typically travels adjacent to injectors, so injectors must be able to withstand high heat flux, temperatures, and pressures.
- **Ideal injector model**
 - Injector face is specified as a wall boundary condition.
 - Injection of the premixture is handled through a source term in the density, momentum, energy, and species equations.
 - We assume complete mixing between the injected mass and the combustion chamber mass within one cell from the injector face.
 - Mass, energy, and momentum of injected mixture is based on assuming sonic conditions (if choked) or subsonic conditions (if unchoked) at the exit plane of the injector.
 - No back flow is allowed.
 - Valid for small area ratio injection walls.



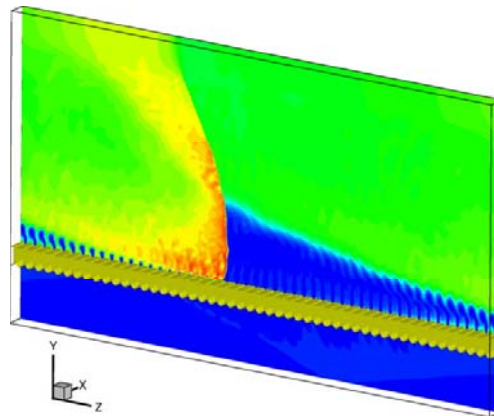
Relevant injection parameters are the throat area to the wall area (A_t/A_w), plenum pressure and temperature.



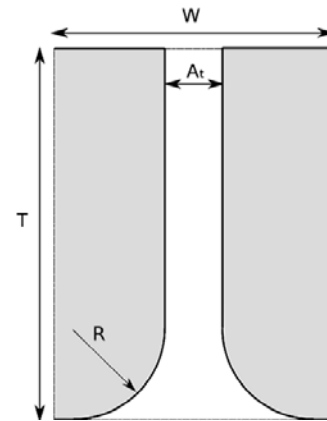


SLOT MICRO-INJECTION SYSTEM

- Two-dimensional simulation
- Slot micro-injector geometry
 - Simulation has a total of 50 micro-injectors, $W=5.457$ mm spacing
 - Plate between plenum and combustion chamber is $T=10$ mm thick
 - Each injector has a throat width of $A_t=1.131$ mm for $a=0.2$, 2.262 mm for $a=0.4$

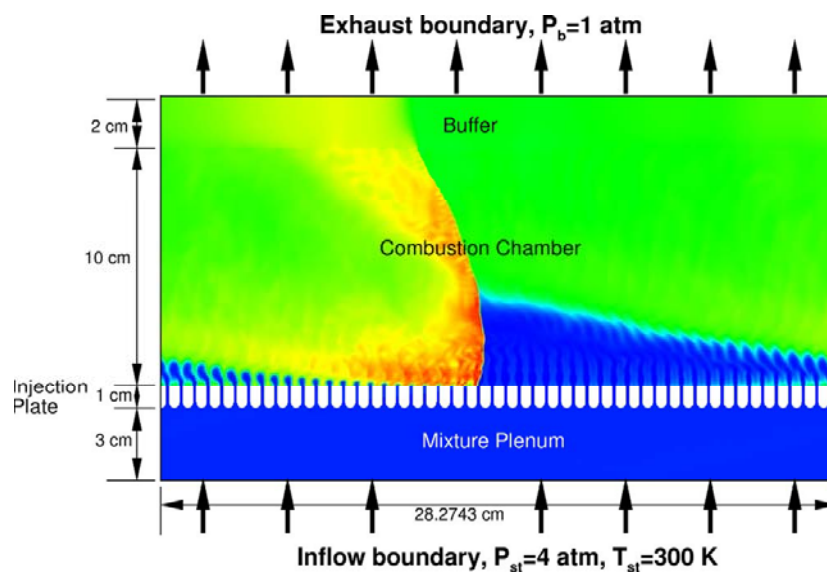


Feedback into Mixture Plenums in RDE's



50th Aerospace Sciences Meeting, January 9-12, 2012

BASELINE RDE GEOMETRY



- 8 cm inner and 10 cm outer diameter
- Base resolution is 0.02 cm, 1.02 million cells for 2D, 51.2 million for 3D
- Injection plate has 50 equally spaced injectors
- Stoichiometric H₂/air mixture flowing into mixture plenum



INLET AREA RATIO EFFECT

Pressure Gain Combustion

Set 1. Constant plenum pressure.

Area Ratio	P_{plenum} (atm)	$P_{t,\text{inlet}}^*$ (atm)	$P_{t,\text{exit}}$ (atm)	% inlet choked
0.1	10	1.79	3.92	87.8%
0.2	10	2.99	6.66	90.7%
0.3	10	4.25	9.39	94.4%
0.4	10	5.35	11.91	94.6%
0.5	10	6.27	14.08	94.9%
0.75	10	8.69	18.38	95.0%

Set 2. Approximately hold mass flow constant.

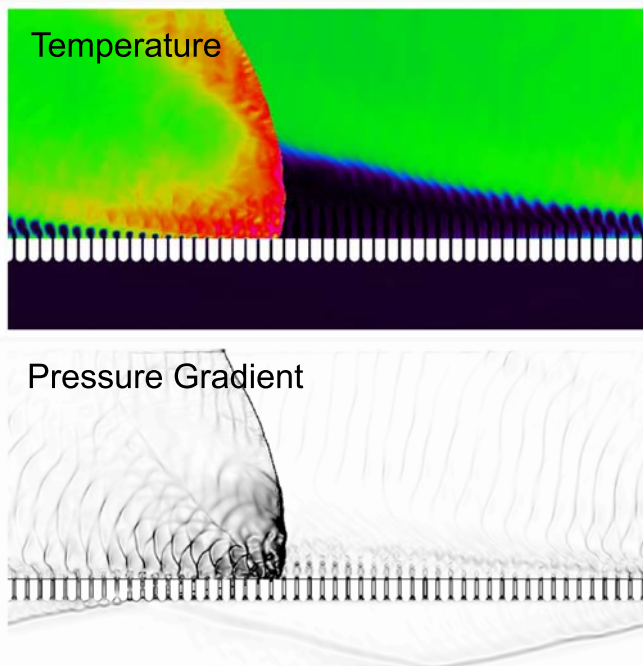
Area Ratio	P_{plenum} (atm)	$P_{t,\text{inlet}}^*$ (atm)	$P_{t,\text{exit}}$ (atm)	% inlet choked
0.1	16.47	3.13	6.59	82.4%
0.2	10.00	2.99	6.66	90.7%
0.3	6.94	3.15	6.72	72.0%
0.4	5.53	3.21	6.55	64.9%
0.5	4.71	3.21	6.78	60.3%
0.75	3.40	3.39	6.21	26.7%

* Inlet pressure only integrated over choked area.

- Above computations demonstrate that for this configuration, to obtain pressure gain combustion, we must have a large ratio of throat area to wall area for the injector face.
- As the area ratio is increased, more feedback can be expected from the combustion chamber detonation wave into the pre-mixture plenum and compressor.
- A better understanding of how to isolate the pre-mixture plenum from the combustion chamber is essential in order to achieve pressure gain combustion.
- The simple mass addition injection model currently used is insufficient for the higher area ratio cases.

SLOT MICRO-INJECTION SYSTEM

Animation to Illustrate Pressure Feedback



Both temperature and pressure show the clear presence of relatively cool jets at the micro-injectors and “dead” zones of higher temperature gas existing between micro-injector jets.

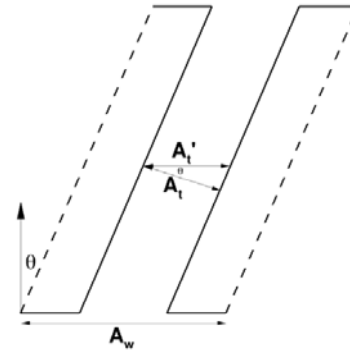
Instantaneous pressure field also shows the presence of a trailing edge shock wave into the mixture plenum.

We have not seen the presence of back flow into the mixture plenum in these cases, although pressure waves can be quite strong.

SLANTED SLOT MICRO-INJECTION SYSTEM Geometry

By slanting the micro-injector with respect to the injection plate and main flow, transverse pressure waves propagating down the injector no longer have a direct line of sight into the mixture plenum.

- $\theta = 0$
Baseline case for comparison.
- $\theta = -20, -40$
Injectors face into the detonation wave, should slow detonation wave.
- $\theta = +20, +40$
Provides maximum shielding of pressure pulses from the detonation wave.



$$A_w = 5.65 \text{ mm}$$

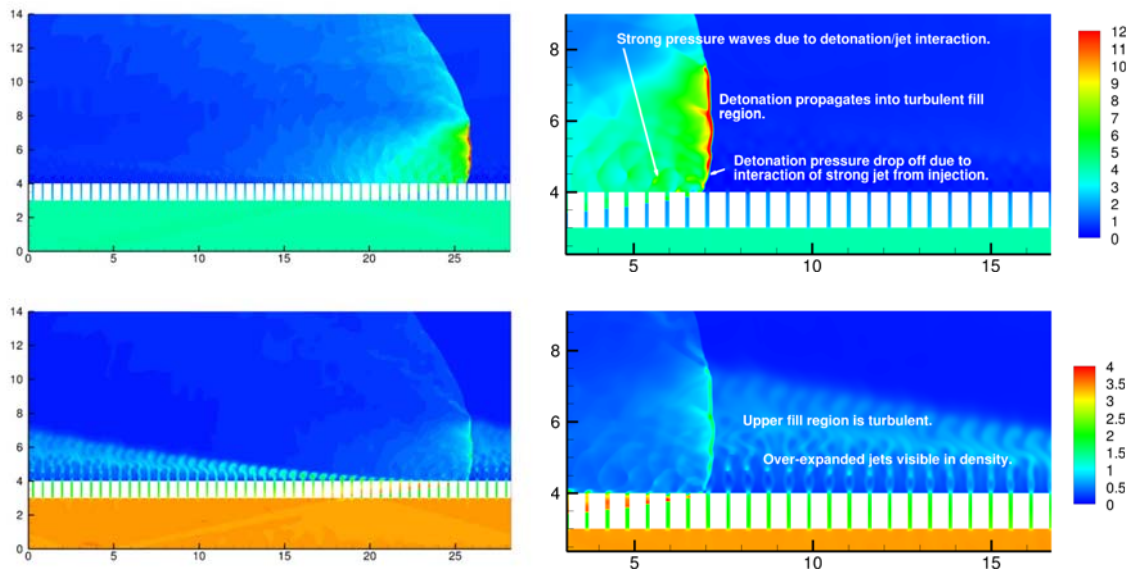
$$A_t = 2.26 \text{ mm } (a=0.4)$$

$$A_t' = 2.405 \text{ mm } (\theta=20),$$

$$2.950 \text{ mm } (\theta=40)$$

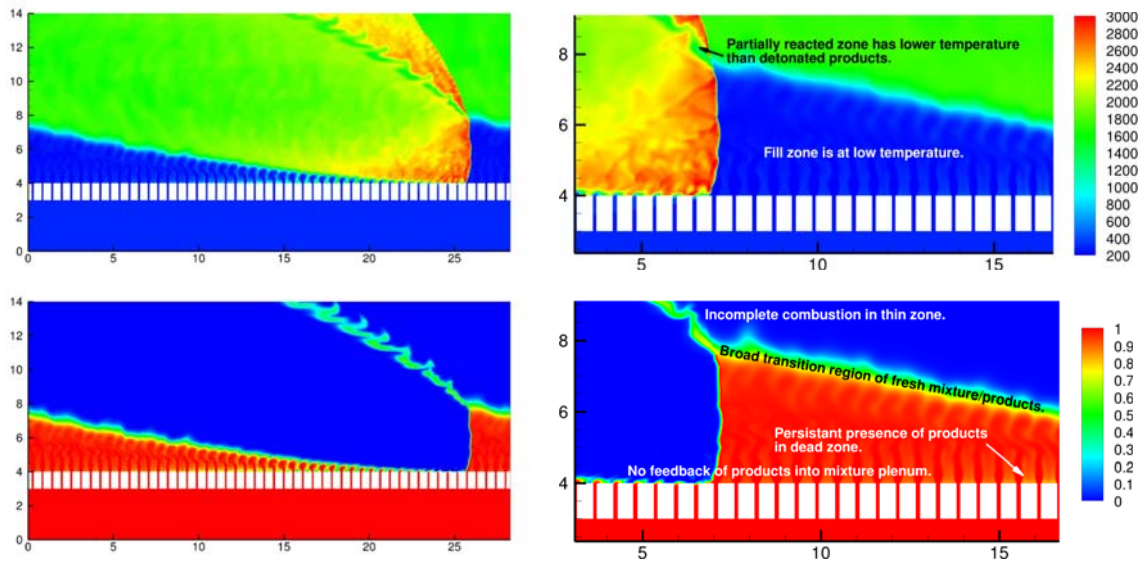
At higher pressures, we see a reversal of the detonation wave for high values of θ .

SLANTED SLOT MICRO-INJECTION SYSTEM Instantaneous Pressure and Density



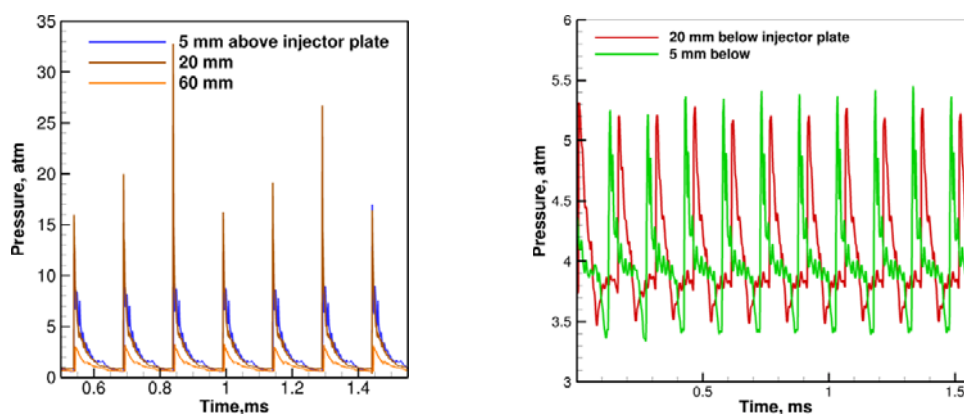
- Detonation is weaker near injection plate
- Density shows fill region inhomogeneity nicely

SLANTED SLOT MICRO-INJECTION SYSTEM Instantaneous Temperature and Reactant



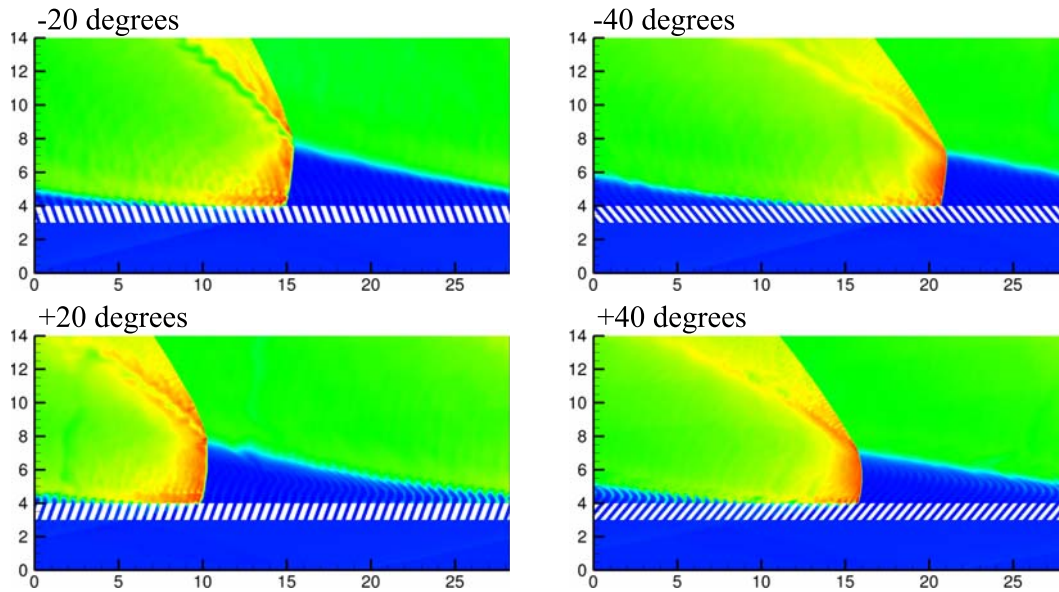
- Temperature shows turbulence in detonation, and unburned region from transition.
- For low pressure cases, we have broad transition region and a small amount of unburned reactants

SLANTED SLOT MICRO-INJECTION SYSTEM Pressure Trace in Mixture Plenum



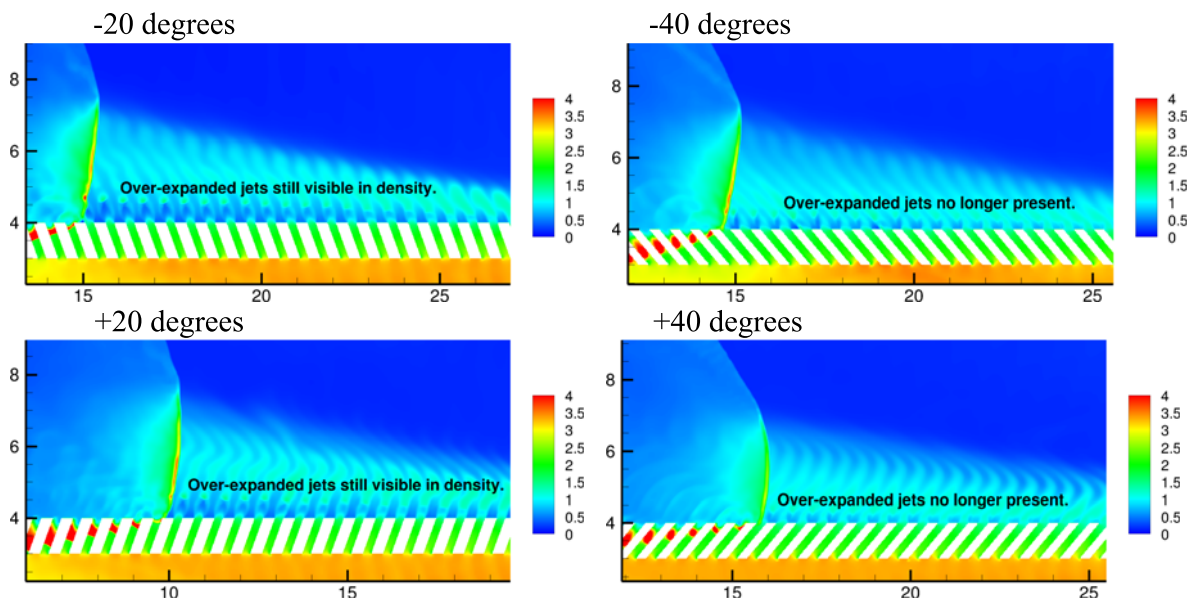
- 5 mm above injector plate does not have extreme pressures seen 20 mm.
- Both overpressures and underpressures exist in the mixture plenum, and are as much as +1.4 atm (+35%) and -0.6 atm (-15%) from the 4 atm stagnation pressure case.

SLANTED SLOT MICRO-INJECTION SYSTEM Instantaneous Temperature



- +40 degree angle no longer has region of unburned reactants
- All cases similar fairly similar temperature field and flow-field features.

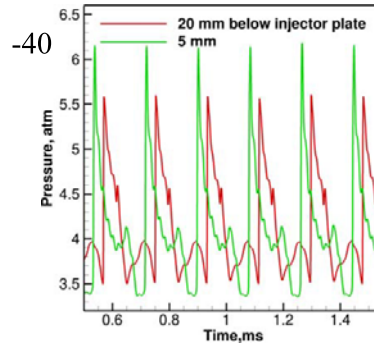
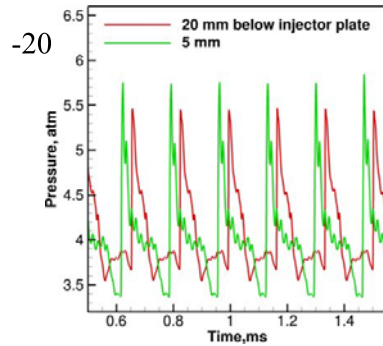
SLANTED SLOT MICRO-INJECTION SYSTEM Instantaneous Density



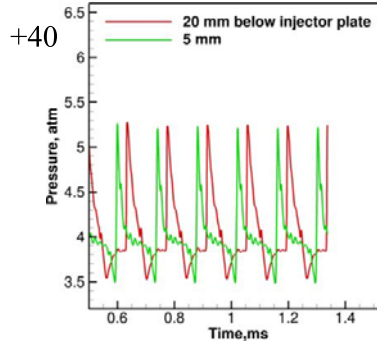
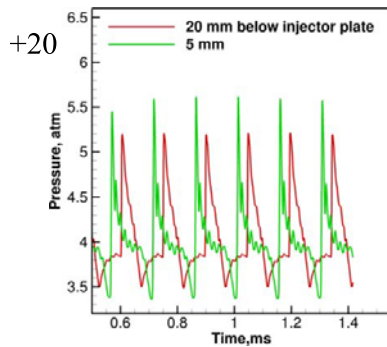
- Both high angle cases have very weak jets or no jets at all from injectors.
- Still see similar striations in the reactant density for all cases.

SLANTED SLOT MICRO-INJECTION SYSTEM

Pressure Trace in Mixture Plenum



Negative slant angles give larger feedback pressures due to how disturbances travel in the flow-field.



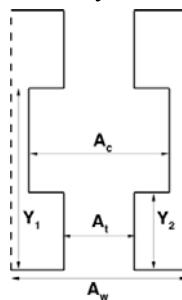
Positive slant angles provide some reduction in the over and underpressure seen in simulations. The overall values are still quite large.

VARIATIONS OF SLOT MICRO-INJECTION SYSTEM

Geometry

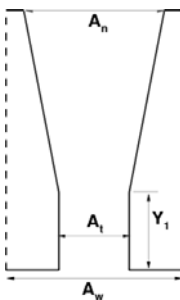
Attempt to modify the injector geometry in order to change flow characteristics in the fill region of the RDE and also the amount of feedback seen in the mixture plenum.

“Cavity Slot”



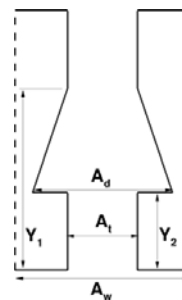
$A_w=5.65$ mm
 $A_t=2.26$ mm
 $A_c=4.52$ mm
 $Y_1=7$ mm
 $Y_2=3$ mm

“Nozzle Slot”



$A_w=5.65$ mm
 $A_t=2.26$ mm
 $A_n=5.65$ mm
 $Y_1=4$ mm

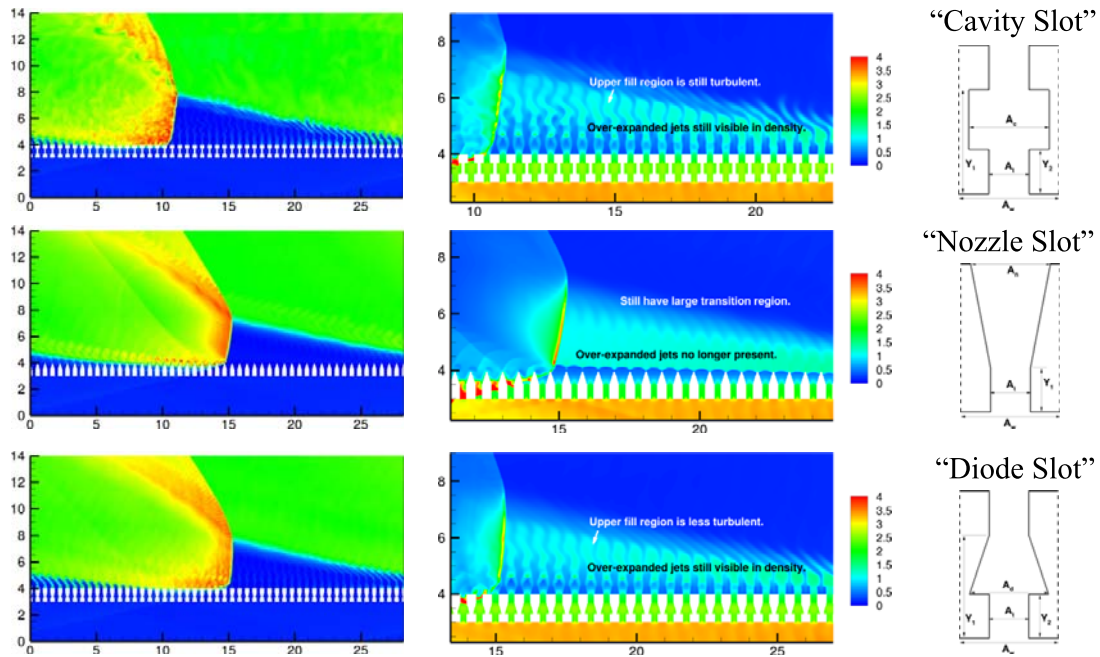
“Diode Slot”



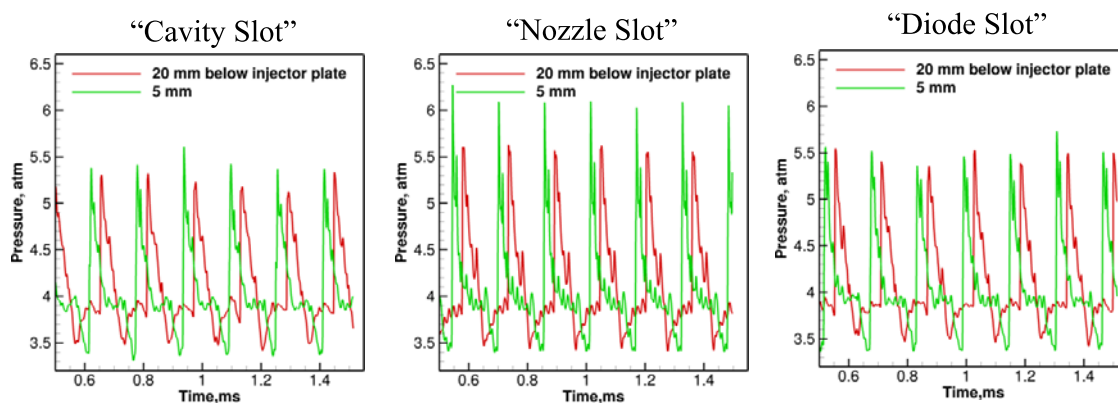
$A_w=5.65$ mm
 $A_t=2.26$ mm
 $A_d=4.52$ mm
 $Y_1=7$ mm
 $Y_2=3$ mm

- **Cavity Slot** - Operates by having a small acoustic cavity within the injector, with some energy of the feedback shock wave dissipating in cavity
- **Nozzle Slot** - Expansion near the combustion chamber to reduce size of dead zones while maintaining same throat area.
- **Diode Slot** - Attempts to create a nozzles such that propagation of waves upward is favorable compared to down into mixture plenum.

VARIATIONS OF SLOT MICRO-INJECTION SYSTEM Instantaneous Temperature and Density



VARIATIONS OF SLOT MICRO-INJECTION SYSTEM Pressure Feedback in Mixture Plenum



- *Cavity Slot* - No substantial improvement in feedback pressure compared to baseline case and produces considerable turbulence in detonation wave.
- *Nozzle Slot* - Removes dead zones and jets in fill region resulting in smoother fill zone and detonation, but is much worse in terms of feedback pressure, since it is more open to the combustion chamber.
- *Diode Slot* - No significant difference in flow-field, but slightly worse than both the cavity slot and baseline case.

SUMMARY PERFORMANCE AND FEEDBACK

Case	D (m/s)	mdot (kg/s)	Thrust (N)	Isp (s)	20 mm below plate		5 mm below plate	
					Pmin(atm)	Pmax(atm)	Pmin(atm)	Pmax(atm)
Slanted slot, angle=0	1879	0.530	594	4040	3.49	5.23	3.40	5.36
Slanted slot, angle=-20	1669	0.510	555	3910	3.60	5.45	3.37	5.77
Slanted slot, angle=+20	1913	0.515	573	4010	3.50	5.22	3.37	5.57
Slanted slot, angle=-40	1554	0.492	532	3900	3.58	5.58	3.37	6.05
Slanted slot, angle=+40	2012	0.502	564	4040	3.53	5.24	3.51	5.22
Cavity slot	1780	0.563	563	3950	3.52	5.26	3.40	5.37
Nozzle slot	1810	0.524	589	4050	3.45	5.61	3.44	6.08
Diode slot	1790	0.521	582	4030	3.52	5.46	3.39	5.49

- Red and green represent minimum/worst and maximum/best values.
- Performance only shows small variation (<4%) between injectors, while mass flow and thrust show larger variations (13.7% and 10.9%)
- No clear winner for reducing feedback pressure, although nozzle slot and negative angle slanted slots are clearly the worst.

Concluding Remarks

- **Rotating Detonation Engine model developed at NRL**
 - Premixed hydrogen-air RDE
 - Low pressure ratio (4), high area ratio (0.4) is regime of interest
 - Baseline RDE geometry with plenum/injection plate simulated
 - Slanted-slot micro-injectors
 - Modifications of slot micro-injectors
“Cavity”, “Nozzle”, and “Diode” modifications
- **Injection system results**
 - Flow-field of different slanted-slot micro-injectors not substantially different
 - Pressure feedback is minimized for positive angle slanted-slot micro-injectors
 - Alternative slot designs modified flow-field in fill region substantially
 - No clear best design for reducing feedback pressure yet, mixed bag
- **Future work Further studies**
 - Evaluate impact of non-premixed injection
 - Further explore different isolating mechanisms and geometries
 - Do full “system” simulation with injection system, combustion chamber, and exit nozzle design.



New Code Development – “PROPEL”

Motivation: Moving forward, we need to be able to work with a wider range of geometries for engines and experiments, and we need to be able to utilize new computational resources that become available quickly while maintaining our ability to simulate detonation and propulsion concepts with the same high fidelity as our previous/current work.

- Based on the Jet-Noise-Reduction (JENRE) code developed at NRL.
- Utilizes GPU's, OpenMP, Thread-Building-Blocks, MPI for HPC
- Hybrid grid representation
 - Cartesian
 - Structured
 - Unstructured
 - Combinations
- Finite volume and finite element representations
- MILES approach using Multi-dimensional Flux-Corrected-Transport (FCT)

Thank You. Questions?